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14. ABSTRACT

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Structural and luminescent properties of bulk InAsSb

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I. INTRODUCTION

Compositionally graded metamorphic buffer layers on InSb and GaSb substrates allow the growth of high quality $InAs_xSb_{1-x}$ films, which is a direct-bandgap, bulk material that can be used for fabrication of infrared (IR) detectors operating in the mid-to-long wave IR range. Bulk $InAs_xSb_{1-x}$ films offer the prospect of a III–V material with sufficiently long minority carrier lifetimes and long carrier diffusion lengths. These parameters currently limit the GaSb/InAs type II strained layer superlattices, which have yet to perform as theoretically predicted, or as well as HgCdTe.[1]

The crystalline quality required for producing photodetectors generally requires lattice matched growth on high quality substrates. Bulk $InAs_{0.91}Sb_{0.09}$ on GaSb substrates has an absorption edge of ~3.8 μm at 100 K. Although InSb has a smaller bandgap, there are no suitable lattice matched wide bandgap alloys available for forming device heterostructures. In order to access longer wavelengths, one must use $InAs_xSb_{1-x}$ alloys having native lattice constants either bigger or smaller than that of GaSb or InSb, respectively.[2–4] Due to the large bowing parameter, $InAs_xSb_{1-x}$ can absorb light at wavelengths beyond 10 μm, but direct growth of these layers onto GaSb or InSb leads to the formation of strain relieving dislocations.[5] A graded buffer approach described by Tersoff[6] allows high quality metamorphic growth of bulk, unstrained, dislocation-free $InAs_xSb_{1-x}$ on either of these commercially available substrates. We recently established the value of this approach in Sb-based materials by fabricating high power As-free diode lasers.[7] In this work, we present the detailed characterization of $InAs_xSb_{1-x}$ alloys, developed within the framework of this technology, that demonstrate strong photoluminescence in the spectral range from 5 to 9 μm.

Growths of $InAs_xSb_{1-x}$ with an absorption edge above 8 μm on GaSb requires the accommodation of a compressive lattice mismatch on the order of 2% or larger, whereas growths on InSb requires less than 2% tensile lattice mismatch accommodation. We have investigated graded buffer layers consisting of GaInSb, AlGaInSb, and InAsSb alloys with variable compositions and, hence, variable native lattice constants. To develop the material technology for detector applications, we minimize the residual strain in thick $InAs_xSb_{1-x}$ absorber layers by mutual optimization of the graded buffer design and absorber layer compositions. For the sake of reaching longer wavelengths in the case of films grown on GaSb, it is more important to reduce the residual strain as compressive strain increases the bandgap. Compressive strain can possibly lead to the Stranski–Krastanov growth mode, although we have seen no case of that in any of the samples grown for this experiment. In the case of growth on InSb, any remaining residual tensile strain is expected to further reduce the bandgap.[8]

II. EXPERIMENT

The heterostructures were grown by solid source molecular beam epitaxy utilizing crackers for As and Sb. The growth temperature was maintained near 415 °C for the $InAs_xSb_{1-x}$ layers grown on GaSb substrates. AlGaInSb graded buffer layers of 2–3.5 μm thick were grown on GaSb at temperatures from 460 to 520 °C. For the InSb substrates the growth temperature was maintained at 395 °C throughout the $InAs_xSb_{1-x}$ graded buffer layer and film growth. The photoluminescence (PL) and absorption spectra were measured with a Fourier-transform infrared spectrometer equipped with a liquid-nitrogen cooled HgCdTe detector with a cutoff wavelength of 12 μm. The PL was excited by a 970 nm laser diode and collected by reflective optics.

III. RESULTS AND DISCUSSION

A. Structural characteristics of graded buffer layers on GaSb substrates

We have grown linearly compositional graded GaInSb and AlGaInSb buffer layers on GaSb substrates. Figure 1 shows a (002) dark field (DF) transmission electron microscope (TEM) image of a $In_xGa_{1-x}Sb$ buffer, where x is linearly graded from 0 to 0.2, developed for the fabrication of an antimonide-based laser diode. The dislocations are present only between the substrate and unrelaxed pseudomorphically strained region of the graded buffer. Using Tersoff's

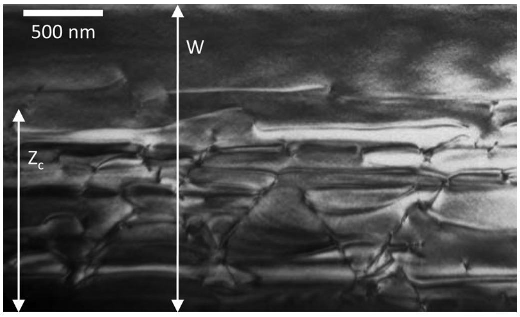

FIG. 1. TEM image of GaInSb graded buffer layer. Similar structures have been grown with $InAs_xSb_{1-x}$ absorption layers on top of the GaInSb graded buffer layer.

nomenclature, Z_c is defined as the distance from the substrate/film interface above which there are few or no dislocations and W is the thickness of the graded layer. In the region between Z_c and W, the topmost part of the graded buffer, the material has a low defect density and remains under compressive strain with an in-plane lattice constant bigger than that of GaSb. An $InAs_{0.77}Sb_{0.23}$ absorber layer can now be grown, as it has a native lattice constant matched to the in-plane lattice constant of the topmost unrelaxed part of this graded buffer layer. We have grown $InAs_{0.80}Sb_{0.20}$ absorption layers on $In_xGa_{1-x}Sb$ buffer layers using the same methodology and obtained similar morphology as shown in Fig. 1, and the optical results are discussed in an upcoming section.

Figure 2 shows a metamorphic heterostructure containing a 1 μm $InAs_{0.80}Sb_{0.20}$ bulk layer grown on top of a 2 μm AlGaInSb linearly compositional graded buffer layer. The native lattice constant of the $InAs_{0.80}Sb_{0.20}$ layer is ~6.14 Å, corresponding to a 0.8% mismatch relative to the GaSb substrate. The native lattice constant of the buffer layer changes from that of GaSb substrate to that of $Al_{0.75}Ga_{0.13}In_{0.12}Sb$ over the 2 μm buffer layer thickness, corresponding to a lattice constant ramp rate of ~0.6 %/μm. The image was taken for a $(1\bar{1}0)$ cross-sectional sample under a (220) bright field two-beam condition. DF images (not shown here) were also collected for multiple two-beam conditions in order to obtain a thorough understanding of the defect morphology as seen for different visibility conditions. The graded composition metamorphic buffer effectively accommodates the lattice mismatch between the GaSb substrate and the $InAs_{0.80}Sb_{0.20}$ film. The residual strain at Z_c is 0.5% and the $InAs_{0.80}Sb_{0.20}$ film is less than 0.1% strained, according to x-ray rocking curve measurements taken for a combination of symmetric and asymmetric reflections, as well as reciprocal space map analysis reported in detail in a prior publication.[2] The topmost section of the graded buffer with $Al_{0.75}Ga_{0.13}In_{0.12}Sb$ composition had a native lattice constant of ~1.3% larger than that of GaSb, but due to compressive strain the in-plane lattice constant is equal to the native constant of the bulk $InAs_{0.80}Sb_{0.20}$ layer. Although the field of view for such a large structure is intrinsically limited in TEM, our image corresponds with the x-ray data in that we do not see any threading dislocations in the $InAs_{0.80}Sb_{0.20}$ layer. From this image and from that obtained from neighboring fields of view, we estimate that the dislocation density is below 10^7 cm^{-2}.

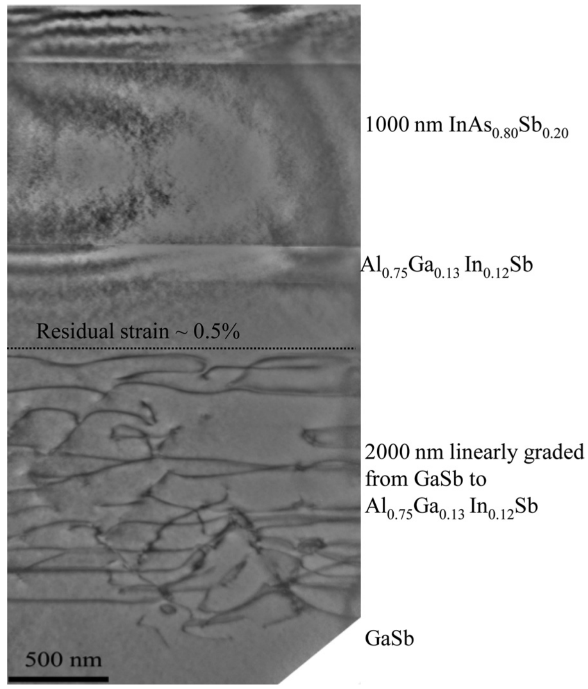

FIG. 2. Metamorphic heterostructure containing a 1 μm $InAs_{0.8}Sb_{0.2}$ bulk layer grown on top of a 2 μm AlGaInSb linearly compositional graded buffer layer.

Figure 3 shows the (004) Ω–2θ high resolution x-ray diffraction (HRXRD) scans for the structure shown in Fig. 2, as well as similar structures grown with $InAs_xSb_{1-x}$ films containing higher Sb concentrations, specifically $x = 0.30$ and 0.44. Although we currently only have TEM data for the $InAs_{0.80}Sb_{0.20}$ film, the x ray results are consistent with similar morphology and extent of strain relaxation for the higher Sb containing samples.

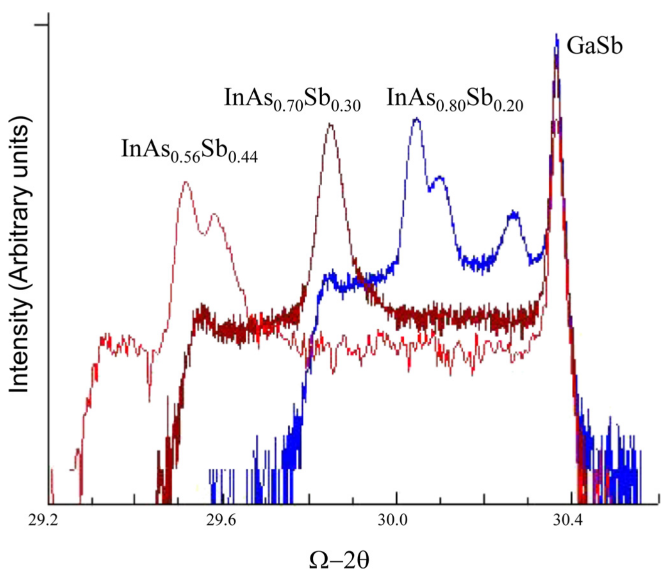

FIG. 3. (Color online) (004) Ω–2θ HRXRD scans for the 1 μm $InAs_{0.80}Sb_{0.20}$ layer, as well as similar structures grown with $InAs_xSb_{1-x}$ films containing higher Sb concentrations, specifically 0.30 and 0.44.

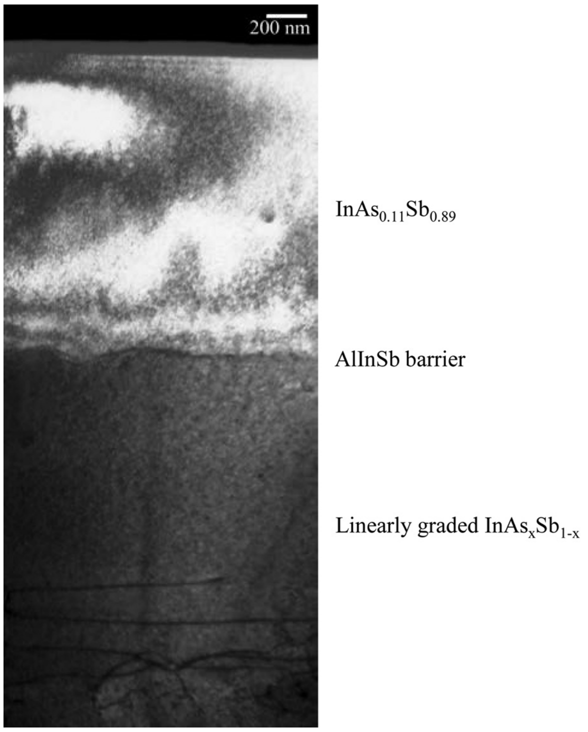

FIG. 4. (220) DF image of an $InAs_{0.11}Sb_{0.89}$ film grown on a $InAs_xSb_{1-x}$ graded buffer layer on a InSb substrate.

B. $InAs_xSb_{1-x}$ grown on InSb substrates

We have also grown $InAs_xSb_{1-x}$ compositionally graded layers on InSb substrates, upon which $InAs_xSb_{1-x}$ absorption layers were grown. X-ray and TEM data indicate that we have grown high quality absorption layers for As concentrations up to 11% for films grown on InSb substrates. A (220) DF image is shown in Fig. 4. Sample preparation damage limited the field of view where the entire structure from substrate to surface was visible, but we were able to examine the top $InAs_xSb_{1-x}$ layer over several lateral microns. No dislocations were observed in the top $InAs_xSb_{1-x}$ layer, and similar to the sample grown on GaSb, we estimate the dislocation density to be below $10^7\,cm^{-2}$.

Figure 5 shows the asymmetric (335) reciprocal space map collected in the [110] direction nearly parallel to the tilt axis (with marginal tilting effect). We find that the bottom part of the graded $InAs_xSb_{1-x}$ buffer layer is nearly fully relaxed and the remaining top portion is partially relaxed. The top $InAs_{0.11}Sb_{0.89}$ layer has an in-plane lattice constant of ~6.45 Å and a perpendicular lattice constant of ~6.42 Å (the native lattice constant for this alloy is ~6.43 Å). This corresponds to an in-plane residual strain of ~0.2%.

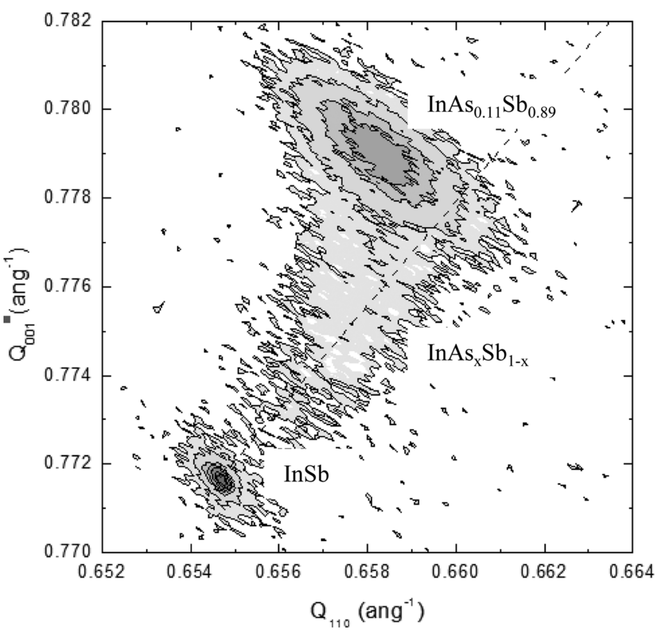

FIG. 5. Reciprocal space maps for the (335) reflections for the $InAs_{11}Sb_{89}$ film grown on an $InAs_xSb_{1-x}$ graded buffer layer on an InSb substrate. The relaxation line is denoted by the dashed line.

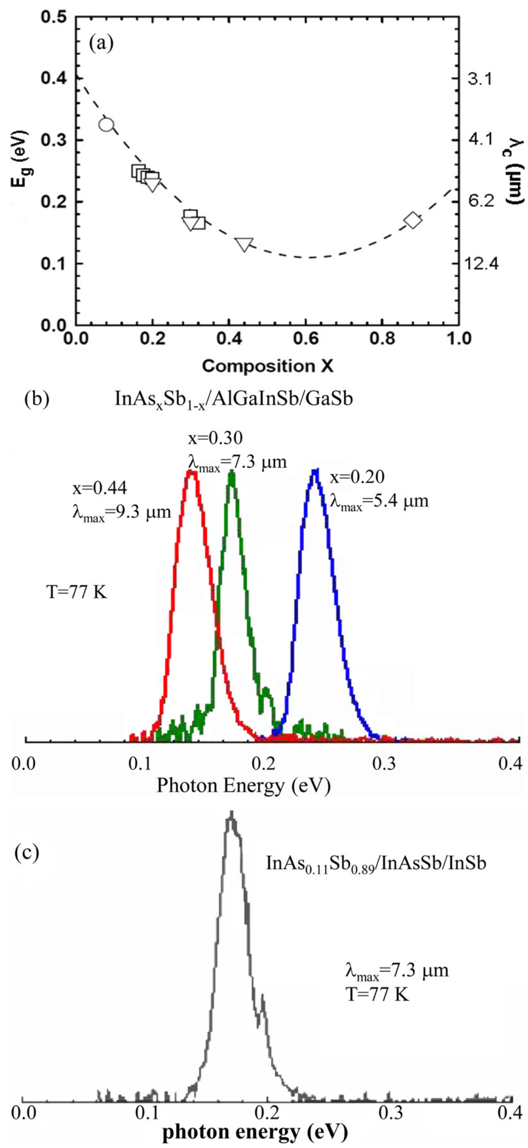

FIG. 6. (Color online) (a) Plot of photoluminescent maximum vs Sb concentration. The circle denotes InAsSb lattice matched to GaSb. The square, triangle, and diamond data points denote InAsSb growths on GaInSb, AlGaInSb, and InAsSb compositionally graded buffer layers, respectively. (b) The PL peaks at 77 K for unrelaxed $InAs_xSb_{1-x}$ layers for $x = 0.20$, 0.30, and 0.44 grown on GaInSb and AlGaInSb buffer layers were 5.4, 7.3, and 9.3 μm. (c) The PL peak at 77 K was at 7.3 μm for $InAs_{11}Sb_{89}$ grown on an $InAs_xSb_{1-x}$ graded buffer layer on a InSb substrate.

C. Optical characterization of $InAs_xSb_{1-x}$ layers

Figure 6 summarizes the PL maxima obtained for $InAs_xSb_{1-x}$ alloys grown on GaInSb and AlGaInSb buffer layers on GaSb substrates and $InAs_xSb_{1-x}$ buffer layers grown on InSb. Neglecting differences between PL maxima and energy gaps as shown in Fig. 6(a), the data points fit the following relationship:

$$E_g(\mathrm{InAs}_{1-x}\mathrm{Sb}_x) = E_g(\mathrm{InAs})(1-x) + E_g(\mathrm{InSb}) \times x - \gamma x(1-x)$$

with the bowing parameter of 0.8 eV, reported previously.[5] Even with the approximation PL max $= E_g$, the bowing parameter is greater than that reported in previous reports on $InAs_xSb_{1-x}$.[9] Figure 6(b) shows that the PL peaks at 77 K for unrelaxed $InAs_xSb_{1-x}$ layers for $x = 0.2$, 0.3, and 0.44 grown on GaInSb and AlGaInSb buffer layers were 5.4, 7.3, and 9.3 μm. Figure 6(c) shows that the PL peak at 77 K was at 7.3 μm for $InAs_{0.11}Sb_{0.89}$ grown on an $InAs_xSb_{1-x}$ graded buffer layer on a InSb substrate.

IV. SUMMARY

We examined a range of compositions of $InAs_xSb_{1-x}$ alloys that allow for sensitivity in the middle and long wave IR range. We used compositionally graded GaInSb, AlGaInSb, and $InAs_xSb_{1-x}$ metamorphic buffer layers to accommodate the misfit strain between the $InAs_xSb_{1-x}$ alloys and GaSb or InSb substrates. All three buffer layer materials successfully mediated the misfit strain and allowed the growth of $InAs_xSb_{1-x}$ alloys with dislocation densities below the minimum amount that could be detected by TEM. We measured PL peaks corresponding to middle and long wavelength IR sensitivity for these high crystalline quality $InAs_xSb_{1-x}$ alloys.

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